

On the outburst amplitude of the soft X-ray transients

T. Shahbaz and E. Kuulkers

University of Oxford, Department of Physics, Nuclear Physics Laboratory, Keble Road, Oxford, OX1 3RH, UK

1 February 2008

ABSTRACT

We find a strong correlation between the optical outburst amplitude ΔV and orbital period P_{orb} for the soft X-ray transient sources with orbital periods less than 1 day. By fitting the observed values for 8 X-ray transients we determine an empirical relation that can be used to predict the orbital period of an X-ray transient given only its outburst amplitude:

$$\Delta V = 14.36 - 7.63 \log P_{orb}(h).$$

For periods less than 12 hrs we determine a relation for the absolute magnitude of the accretion disc during outburst, which then allows us to estimate the distances to the sources.

Key words: binaries: close – accretion, accretion disc – stars: neutron – novae, cataclysmic variables – X-rays: stars

1 INTRODUCTION

The soft X-ray transients (SXTs) are a sub-class of the low-mass X-ray binaries (LMXBs), in which a Roche-lobe overflowing, main sequence or subgiant star, typically $< 1M_{\odot}$, orbits a neutron star or black hole, with an orbital period of a few hours to a few days. The SXTs undergo episodic periods of X-ray and optical outbursts, which are separated by long intervals (several decades) of quiescence.

The most fundamental parameter is the orbital period, which sets the size and evolutionary state of the system. However, one can only determine the orbital period of the SXTs when they have subsided into quiescence (unless the system is eclipsing). It is only then one can undertake a radial velocity study of the secondary star in order to determine the orbital period. Even then, some systems (e.g. GS1354–64 and A1524–617) are just too faint to obtain radial velocity curves with conventional sized telescopes (van Paradijs & McClintock 1994).

In this letter we derive an empirical formula that allows us to estimate the orbital period of a SXT given only the size of the optical outburst amplitude.

2 THE OUTBURST AMPLITUDE–ORBITAL PERIOD RELATION

In Table 1 we give the general properties of the SXTs. During quiescence many of the sources show changes in the mean brightness from year to year, combined with the fact that in some the optical nova was not discovered optically until several days after the initial X-ray outburst. We therefore esti-

mate typical errors for the outburst amplitude to be around 0.2 magnitudes. In Fig. 1 we show the relation between orbital period and the amplitude of the optical outburst. There is only a lower limit to the quiescent magnitude of EXO0748–676, therefore it is not included in Fig. 1. We find that as the orbital period increases, the amplitude of the outburst decreases. Such a correlation is not unexpected, as this reflects the fact that at longer orbital periods, the secondary star is larger and hence more luminous than a system at a shorter orbital period. The only systems that do not fit this correlation are the extremely long period systems GROJ1655–40 and GS2023+338; which both have periods greater than 1 day. Both systems have secondary stars sufficiently evolved from the main sequence that one cannot compare them to the other transients. Therefore in what follows we restrict ourselves to those transients with orbital periods less than 1 day.

For $P_{orb}(h) \lesssim 24$ we find that the ΔV – $\log P_{orb}(h)$ relationship is well represented by a linear least-squares fit of the form

$$\Delta V = 14.36(\pm 0.78) - 7.63(\pm 0.75) \log P_{orb}(h) \quad (1)$$

which has a correlation coefficient of -0.93 (The $1\text{-}\sigma$ errors were calculated after rescaling the error bars to give a fit with χ^2_{ν} of 1).

Using equation (1) it is therefore possible to estimate the orbital period of a transient given only the observed values for its outburst amplitude.

Table 1. General properties of X-ray Novae

Source	X-ray Nova Designation	Orbital Period (hrs)	V (mags) quiescence	V (mags) outburst	E_{B-V} (mags)	Distance (kpc)	References
GROJ0422+32	Nova Per 1992	5.09	22.4	13.2	0.30	2.0	1–4
A0620–00	Nova Mon 1975	7.75	18.3	11.2	0.35	1.1	5–8
EXO0748–676		3.82	>23	16.9	0.42	7.6	9–13
GRS1009–45	Nova Vel 1993	6.86	21.4–21.9	13.8	0.20	1.5–4.5	14–16
GRS1124–68	Nova Mus 1991	10.38	20.33	13.5	0.29	3.0–5.5	17–20
4U1456–32	Nova Cen 1969	15.10	18.7	12.8	0.10	1.2	21–24
H1705–250	Nova Oph 1977	12.55	21.5	15.8	0.45		25–27
4U1908+005		18.97	19.2	14.8	0.35	2.5	28–29
GS2000+25	Nova Vul 1988	8.26	25.2	16.4	1.70	2.0	30–34
GROJ1655–40	Nova Sco 1994	62.92	17.2	14.0	1.3	3.2	35–38
GS2023+338	Nova Cyg 1989	155.31	18.4	12.5	1.0	2.2–3.7	39–42

- (1) Castro-Tirado, Pavlenko, Shlyapnikov, Brandt, Lund, Ortiz 1993
(2) Zhao 1994
(3) Filippenko, Matheson & Ho 1995
(4) Beekman, Shahbaz, Naylor, Charles, Wagner, Martini 1997
(5) Wu, Panek, Holm, Schmitz 1983
(6) McClintock & Remillard 1986
(7) Haswell, Robinson, Horne, Stiening, Abbott 1993
(8) Shahbaz, Naylor & Charles 1994
(9) Pederson & Mayor 1985
(10) Wade, Quintana, Horne, Marsh 1985
(11) Parmar, White, Giommi, Gottwald 1986
(12) Schoembs & Zoeschinger 1990
(13) van Paradijs & White 1995
(14) Della Valle & Benetti 1993
(15) Shahbaz, van der Hooft, Charles, Casares, van Paradijs 1996
(16) Della Valle, Benetti, Cappellaro, Wheeler 1997
(17) Della Valle, Jarvis & West 1991 &
(18) Cheng, Horne, Panagia, Shrader, Gilmozzi, Paresce, Lund 1992
(19) Orosz, Charles, McClintock, Remillard 1996
(20) Shahbaz, Naylor & Charles 1997
(21) Canizares, McClintock & Grindlay 1980
(22) Blair, Raymond, Dupree, Wu, Holm, Swank 1984
(23) Shahbaz, Naylor & Charles 1993
(24) McClintock & Remillard 1990
(25) Griffiths et al., 1978
(26) Remillard, Orosz, McClintock, Bailyn 1996
(27) Filippenko, Matheson, Leonard, Barth, van Dyk 1997
(28) Charles et al., 1980
(29) Chevalier & Ilovaisky 1991
(30) Chevalier & Ilovaisky 1990
(31) Callanan & Charles 1991
(32) Charles, Kidger, Pavlenko, Prokofieva, Callanan 1991
(33) Filippenko, Matheson & Barth 1995
(34) Callanan, Garcia, Filippenko, McClean, Teplitz 1996
(35) Bailyn et al., 1995
(36) Hjellming & Rupen 1995
(37) Horne et al., 1996
(38) Orosz & Bailyn 1997
(39) Wagner, Kreidl, Howell, Collins, Starrfield 1989
(40) Shahbaz, Ringwald, Bunn, Naylor, Charles, Casares 1994
(41) Casares & Charles 1994
(42) Casares, Charles, Naylor, Pavlenko 1993

3 APPLICATION

For some of the X-ray transients, their quiescent magnitudes have proved too faint for one to obtain accurate radial velocity or photometric light curves of the secondary star, which will allow one to determine the orbital period of these systems. In the next section we estimate quiescent magnitudes and/or the orbital periods of a few of the faint transients.

3.1 EXO0748–676

For a Roche-lobe filling star the average density, ρ is simply a function of the orbital period (Frank, King & Raine 1985). For EXO0748–676 with $P_{orb}=3.82$ hrs, $\rho=7.54$ g cm $^{-3}$, which implies a M3–4V star (Allen 1981). This can be compared with the spectral type of the secondary star obtained by determining its absolute magnitude. Using equation (4) we find $M_v(2)=10.2$ mags, which implies an M2–3 V star (Allen 1981).

Using equation (1) we can also predict the quiescent magnitude of EXO0748–676. With $V_O=16.9$, we find $V_Q \sim 26.8$ mags, which is consistent with the observed limit of $V_Q > 23$ mags (see Table 1). However, if the secondary star is sufficiently evolved for it to be degenerate, then it would not obey equation (4) and would probably be fainter. Note

that the models of King, Kolb & Burderi (1996) show that neutron-star SXTs may require evolved companions, even at short orbital periods.

3.2 GRS1354–64(=Nova Cen 1967)

We can estimate the orbital period for GRS1354–64 by using equation (1). Since there are no V-band measurements for the system in quiescence, we use the colors of a K0–M0 star in order to determine V_Q . Using $R_Q=20.3$ mags (Martin 1996), $E_{B-V}=1.0$ mags (van Paradijs & McClintock 1994) and $(V-R)=0.6$ – 1.2 mags (K0–M0V/III; Allen 1981), we estimate $V_Q=21.6$ – 22.2 mags. Then using equation (1) with $V_O=16.9$ mags (Pederson, Ilovaisky & van der Klis 1987) gives $\Delta V=4.7$ – 5.3 mags and hence $P_{orb}=15.4$ – 18.5 hrs, which is consistent with that obtained by Martin (1996); 15.6 hrs.

3.3 GRS1716–249(=Nova Oph 1993)

Masetti et al. (1996) interpret a 14.7 hr periodicity as the superhump period. If this interpretation is correct, then the true orbital period should be a few percent shorter. Using equation (1) with $V_O=16.3$ mags and $V_Q > 21$ mags (Della

Valle, Mirabel & Rodriguez 1994) we estimate $P_{orb} < 18.5$ hrs, which is consistent with the superhump period.

4 THE ABSOLUTE MAGNITUDE OF THE ACCRETION DISC

The amplitude of the optical outburst, Δ is the difference in magnitudes between the system in quiescence and in outburst,

$$\Delta V = V_Q - V_O = M_Q - M_O, \quad (2)$$

where V_Q and M_Q are the apparent and absolute magnitudes of the system in quiescence, respectively, and V_O and M_O are the apparent and absolute magnitudes of the system in outburst, respectively.

In outburst the hot accretion disc dominates the optical flux [$m_v(disc)$], whereas in quiescence the observed optical flux arises from the secondary star [$m_v(2)$] and the contribution from the cool accretion disc. The magnitude of the system in quiescence V_Q is given by $m_v(2) + 2.5 \log f$, where f is the fraction of light arising from the secondary star; $f=1.0$ implies all the optical flux in quiescence come from the secondary stars. Typically f is about 0.5, i.e. 50% of the light comes from the secondary star (Chevalier & Ilovaisky 1989; McClintock & Remillard 1986; and Charles 1996). We can therefore write

$$\begin{aligned} \Delta V &= m_v(2) + 2.5 \log f - m_v(disc) \\ &= M_v(2) + 2.5 \log f - M_v(disc). \end{aligned} \quad (3)$$

Warner (1987, 1995) finds that the luminosity of the companion stars in cataclysmic variables ($P_{orb} \lesssim 10$) are indistinguishable from main sequence stars. The secondary stars in LMXBs with orbital periods $\lesssim 12$ hrs will also lie on the main sequence or the terminal age main sequence (Shahbaz, Naylor & Charles 1997), and so we extend Warner's relation to 12 hrs. He finds that the absolute magnitude of the secondary star can be represented by

$$M_v(2) = 16.7 - 11.1 \log P_{orb}(h). \quad (4)$$

Unfortunately, a similar relationship does not exist for evolved stars, therefore the following is only applicable for systems with un-evolved secondaries, i.e. systems with $P_{orb} \lesssim 12$ hrs.

Since we have relationships for ΔV and $M_v(2)$ as functions of the orbital period ($P_{orb}(h) \lesssim 12$), we can then derive a similar relationship for $M_v(disc)$

$$\begin{aligned} M_v(disc) &= M_v(2) - \Delta V + 2.5 \log f \\ &= 2.34(\pm 0.78) - 3.47(\pm 0.75) \log P_{orb}(h) \\ &+ 2.5 \log f. \end{aligned} \quad (5)$$

As the orbital period increases, the size of the system also increases. If we assume that during outburst the size of the accretion discs in SXTs are similar i.e. the accretion discs extends out to the tidal radius, then one expects the accretion disc during outburst to brighten as the orbital period of the system increases, simply because of the increase in the projected surface area of the accretion disc.

Equation (5) can be compared with the formula give by van Paradijs & McClintock (1994). They determine a

relationship between the absolute magnitude of the accretion disc, X-ray luminosity and orbital period for SXTs in outburst and LMXBs. We can rewrite their equation as

$$M_v(disc) = 1.57 - 1.51 \log P_{orb}(h) - 1.14 \log(L_X/L_{Edd}) \quad (6)$$

where L_X is the outburst X-ray luminosity and L_{Edd} is the Eddington limited luminosity for a $1.4 M_\odot$ neutron star. (It should be noted that, although van Paradijs & McClintock included the black hole candidates A0620-00 and GS2023+338, removing these points does not change the correlation significantly.) Chen, Shrader & Livio (1997) tabulate $\log(L_X/L_{Edd})$ for all the LMXBs and SXTs in outburst, where in this case L_{Edd} is the Eddington limiting for an object with general mass M . By fitting the data points for systems with orbital periods less than 12 hrs, we obtain a linear least-squares fit of the form

$$\log(L_X/L_{Edd}) = 3.63(\pm 0.90) \log P_{orb}(h) - 4.20(\pm 1.02). \quad (7)$$

From equations (6) and (7) we obtain the absolute magnitude of the accretion disc as a function of orbital period:

$$M_v(disc) = 6.36(\pm 1.36) - 5.65(\pm 1.20) \log P_{orb}(h). \quad (8)$$

As one can see the gradients of equation (5) and (8) are comparable (at the 90 per cent confidence level). However, unlike the correlation derived by van Paradijs & McClintock (1994), the relation we obtain for the absolute magnitude of the accretion disc does not depend on the distance and reddening to the SXT. We therefore believe that equation (5) is a better representation of the absolute magnitude of the accretion disc in LMXB for systems with $P_{orb}(h) \lesssim 12$.

It is interesting to compare the absolute magnitudes of the accretion discs in dwarf novae and SXTs in outburst. By manipulating equation (13) of Warner (1987) for the absolute magnitude of accretion discs in dwarf novae at maximum light, we find

$$M_v(disc, WD) = 6.0 - 2.69 \log P_{orb}(h). \quad (9)$$

Comparing this with equation (5), we find for a given orbital period, the accretion discs in SXTs during outburst are more than 4 magnitudes brighter (depending on the value for f) than dwarf novae at maximum light, which is typically what is expected (van Paradijs & McClintock 1994). We note that this is similar to the difference of the mean absolute magnitudes derived for persistent LMXBs and CVs (e.g. novae-like; see van Paradijs & Verbunt 1984). This difference in brightness has a natural explanation in that accretion discs of SXTs in outburst and persistent LMXBs are dominated by X-ray irradiation, whereas the discs in CVs are not (see e.g. van Paradijs & Verbunt 1984 and van Paradijs & McClintock 1994). However, it should be noted that the orbital separation of the SXTs, (most of which are black holes) are probably a factor 2 larger at a given period, therefore disc area is 4 times larger than in the dwarf novae. This combined with the fact that the accretion rate of a SXT disc in outburst is an order of magnitude higher than in a dwarf nova at a given period may partly explain the difference in accretion disc magnitudes.

Table 2. Distance estimate for transients with $P_{orb}(h) < 12$ and $f=1.0$

Source	P_{orb} (hrs)	V (mags) outburst	A_v (mags)	Distance (kpc)
EXO0748-676	3.82	16.9	1.3	11.4 ± 2.0
GROJ0422+32	5.09	13.2	0.9	3.0 ± 0.6
GRS1009-45	6.86	13.8	0.6	5.7 ± 1.1
A0620-00	7.75	11.2	1.1	1.5 ± 0.3
GS2000+25	8.26	16.4	5.32	2.4 ± 0.5
GRS1124-68	10.38	13.5	0.9	5.7 ± 1.2

5 THE DISTANCE-PERIOD RELATION

We can now use equation (5) along with the distance modulus equation to obtain an expression for the distance to the X-ray transients ($P_{orb}(h) \lesssim 12$) as a function of orbital period:

$$\begin{aligned} 5 \log D_{kpc} &= V_O - A_v - 2.5 \log f \\ &- 12.34 + 3.47 \log P_{orb}(h), \end{aligned} \quad (10)$$

where D_{kpc} is the distance in kpc and A_v is the reddening.

In Table 2 we estimate the distances for 7 transients using this relation (we have assumed $f=1.0$, so the distance estimates are lower limits). As one can see for most of the systems our estimates agree quite well with the values in the literature (see Table 1). We note, however, that the main uncertainty in determining the distance is the value used for the reddening.

6 CONCLUSIONS

By fitting the outburst amplitudes for 8 X-ray transients we determine an empirical relation that can be used to predict the orbital period of an X-ray transient. Also, for periods below less than 12 hrs we determine a relation for the absolute magnitude of the accretion disc during outburst, which allows us to estimate the distances to the sources.

ACKNOWLEDGEMENTS

We would like to thank Phil Charles for valuable discussions and the referee, Andrew King for his careful reading of the manuscript. The figure was plotted using the ARK software on the Oxford Starlink node.

REFERENCES

Allen C.W., 1981, *Astrophysical Quantities*, 3rd edn, Athlone Press, London
 Bailyn C.D., et al., 1995, *Nat*, 374, 701
 Beekman G. Shahbaz T., Naylor T., Charles P.A., Wagner R.M. Martini P., *MNRAS*, 1997, in press
 Blair W.P., Raymond J.C., Dupree A.K., Wu C.-C., Holm A.V., Swank J.H., 1984, *ApJ*, 278, 270
 Canizares C. R., McClintock J. E., Grindlay J. E., 1980, *ApJ*, 236, L55
 Castro-Tirado A.J., Pavlenko E.P., Shlyapnikov A.A., Brandt S., Lund N., Ortiz J.L., 1993, *A&A*, 276, L37
 Callanan P.J., Charles P.A., 1991, *MNRAS*, 249, 573

Callanan P.J., Garcia M.R., Filippenko A.V., McClean I., Teplitz H., 1996, *ApJ*, 470, L57
 Casares J., Charles P.A., Naylor T., Pavlenko E.P., 1993, *MNRAS*, 265, 834
 Casares J., Charles P.A., 1994, *MNRAS*, 271, L5
 Charles P.A., et al., 1980, *ApJ*, 237, 154
 Charles P. A., Kidger M. R., Pavlenko E. P., Prokofieva V. V., Callanan P. J., 1991, *MNRAS*, 249, 567
 Charles P.A., 1996, in *Compact Stars in Binaries*, eds J.van Paradijs, E.P.J.van den Heuvel, E.Kuulkers, IAU Symp 165, 341
 Chen W., Shrader C.R., Livio M., 1997, *ApJ*, in press
 Cheng 1992 F.H., Horne K., Panagia N., Shrader C.R., Gilmozzi R., Paresce F., Lund N., 1992, *ApJ*, 397, 664
 Chevalier C., Ilovaisky S.A., 1989, *A&A*, 210, 114
 Chevalier C., Ilovaisky S.A., 1990, *A&A*, 238, 163
 Chevalier C., Ilovaisky S.A., 1991, *A&A*, 251, L11
 Della Valle M., Jarvis B.J., West R.M., 1991, *Nat*, 353, 50
 Della Valle & Benetti 1993 *IAUC* 5890
 Della Valle M., Mirabel I.F., Rodriguez L.F., 1994, *A&A*, 290, 803
 Della Valle M., Benetti S., Cappellaro E., Wheeler C., 1997, *A&A*, 218, 179
 Filippenko A.V., Matheson T., Barth A.J., 1995, *ApJ*, 455, L139
 Filippenko A.V., Matheson T., Ho, L.C., 1995, *ApJ*, 455, 614
 Filippenko A.V., Matheson T., Leonard D.C., Barth A., van Dyk, 1997, *PASP*, 109, 461
 Frank J., King A.R., Raine D.J., 1985 in *Accretion power in Astrophysics*, Cambridge University press
 Griffiths R.E., et al., 1978, *ApJ*, 221, L63
 Haswell C.A., Robinson E.L., Horne K., Stiening R.F., Abbott T.M.C., 1993, *ApJ*, 411, 801
 Horne et al. 1996, *IAUC* 6406
 Hjellming R.M., Rupen M.P., 1995, *Nature*, 375, 464
 King A.R., Kolb U., Burderi L., 1996, *ApJ*, L127
 Martin A.C., 1996, PhD thesis, Univ. Oxford
 Masetti N., Bianchini A., Bonibaker J., Della Valle M., Vio R., 1996, *A&A*, 314, 123
 McClintock J.E., Remillard R.A., 1986, *ApJ*, 308, 110
 McClintock J.E., Remillard R.A., 1990, *ApJ*, 350, 386
 Orosz J.A., Charles D.B., McClintock J.E., Remillard R.A., 1996, *ApJ*, 468, 380
 Orosz J.A., Bailyn C.D., 1997, *ApJ*, 477, 876
 Parmar A.N., White N.E., Giommi P., Gottwald M., 1986, *ApJ*, 308, 199
 Pederson H., Mayor M., 1985, *IAUC* 4039
 Remillard R.A., Orosz J.A., McClintock J.E., Bailyn C.D., 1996, *ApJ*, 459, 226
 Horne et al. 1996, *IAUC* 6406
 Hjellming R.M., Rupen M.P., 1995, *Nature*, 375, 464
 Schoembs R., Zoeschinger G., 1990, *A&A*, 227, 105
 Shahbaz T., Naylor T., Charles P.A., 1993, *MNRAS*, 265, 625
 Shahbaz T., Naylor T., Charles P.A., 1994, *MNRAS*, 268, 756
 Shahbaz T., Ringwald F.A., Bunn J.C., Naylor T., Charles P.A., Casares J., 1994, *MNRAS*, 271, L10
 Shahbaz T., van der Hooft F., Charles P.A., Casares J., van Paradijs J., 1996, *MNRAS*, 282, L47
 Shahbaz T., Naylor T., Charles P.A., 1997, *MNRAS*, 285, 607
 van Paradijs J., McClintock J.E., 1994, *ApJ*, 290, 113
 van Paradijs J., White N.E., 1995, *ApJ*, 447, L33
 van Paradijs J., Verbunt 1984, in *AIP Conf. Proc.*, 115, *High Energy Transients in Astrophysics*, ed. S.E. Woosley, New York, 49
 Wade R.A., Quintana H., Horne K., Marsh T., 1985, *PASP*, 97, 1092
 Wagner R.M., Kreidl T.J., Howell S.B., Collins G.W., Starrfield S.G., 1989, *IAUC* 4987

- Warner B., 1995, in Cataclysmic Variable Stars, Cambridge University Press, 117
Warner B., 1987, MNRAS, 227, 23
Wu C.C, Panek R.J., Holm A.V., Schmitz M., 1983, PASP, 95, 391
Zhao P., 1994 IAUC 6072

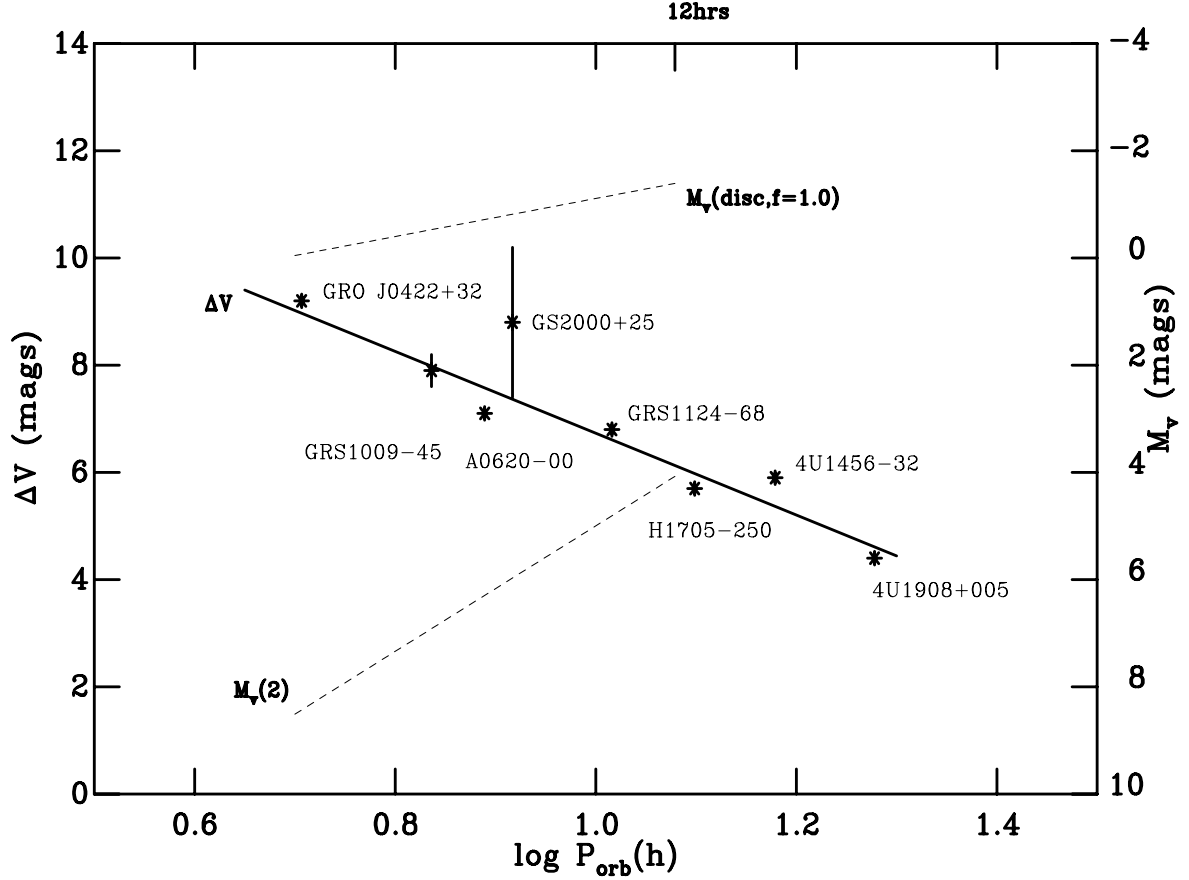


Figure 1. Shown is the V-band outburst amplitude versus orbital period for the soft X-ray transients with orbital periods less than 1 day. For GRS1009-45 and GS2000+25 the V-band magnitude in quiescence was estimated using the spectral type of the secondary star; the large uncertainty is due to the poorly constrained reddening. The solid line is the least-squares fit to the data points. For systems with periods less than 12 hrs we also plot (dashed lines) relations for the absolute magnitude of the accretion disc in an outbursting SXT (assuming the secondary star dominates in quiescence, i.e. $f = 1$) and the absolute magnitude of the secondary star (Warner 1995). If the secondary star does not dominate in quiescence the SXT disc is even brighter ($f < 1$). The outburst amplitude versus orbital period correlation is due to the secondary star brightening faster than the accretion disc, as the orbital period increases.